Telerobotic Excavation System for Unexploded Ordnance Retrieval

B. L. Burks, S. M. Killough, D. H. Thompson,
Robotics & Process Systems Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6304

R. A. Rossi
Office of the Project Manager for Ammunition Logistics
Picatinny Arsenal, New Jersey 07801-5001

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ABSTRACT

The small emplacement excavator (SEE) is a ruggedized military vehicle with backhoe and front loader used by the U.S. Army for unexploded ordnance (UXO) retrieval and general utility excavation activities. In order to evaluate the feasibility of removing personnel from the vehicle during high-risk excavation tasks a development and demonstration projec was initiated to evaluate performance capabilities of the SEE under telerobotic control. Development of a telerobotic SEE (TSEE) was performed by the Oak Ridge National Laboratory (ORNL) in a project funded jointly by the U.S. Army, Project Manager for Ammunition Logistics (PM-AMMOLOG) and the U.S. Department of Energy, Office of Technology Development, Robotics Technology Development Program. The TSEE features teleoperated driving, a telerobotic backhoe with four degrees-of-freedom, and a teleoperated front loader with two degrees-of-freedom on the bucket. Remote capabilities include driving (forward, reverse, brake, and steering), power takeoff shifting to enable digging modes, deploying stabilizers, excavation and computer system booting. The system is operated with an intuitive hand controller at a remotely located portable, suitcase-size base station.

A technology demonstration of the TSEE was conducted at McKinley Range, Redstone Arsenal, Huntsville, Alabama on 13-17 September, 1993. The primary objective of the demonstration was to evaluate and demonstrate the feasibility of remote UXO retrieval. During the demonstration, explosive ordnance disposal specialists were instructed on telerobotic operation of the TSEE, and then were asked to complete a simulated UXO retrieval task. Participants then submitted an evaluation of the system including human factors performance data. This presentation will describe the TSEE, retrieval demonstration, and summarize results of the performance evaluations. Some examples of the results are given below. Seventy percent of the demonstration participants found the tasks were as easy or easier to accomplish utilizing the remote system than with an unmodified system. Similarly, eighty percent of the participants found the TSEE hand controller was as easy or easier to use than the normal manual controls.

1. INTRODUCTION

The Telerobotic Small Emplacement Excavator (TSEE) was developed at the Oak Ridge National Laboratory (ORNL) in a joint project funded by the U. S. Department of Energy (DOE) Office of Technology Development (OTD), Robotics Technology Development Program and the U.S. Army, Project Manager for Ammunition Logistics (PM-AMMOLOG), Picatinny Arsenal. The primary DOE interest in the project is the application of remote excavation controls technology to buried waste removal. The U.S. Army's primary interest is to utilize the technology for retrieval of unexploded ordnance; however, a secondary application with huge potential is range clearance. The remotely operated excavator decreases the need for human intervention at hazardous work sites, making it attractive for a variety of commercial uses as well. The TSEE project and potential applications have been described in brief form elsewhere [1-5]. Results of the human factors tests conducted at the Redstone Arsenal have not previously been presented at a conference or symposium, but have been published in a detailed technical report [6]. Videotapes describing the work and a detailed technical report of buried waste retrieval tests are also available [7-9].

2. REMOTE EXCAVATION TECHNOLOGY DEMONSTRATIONS

2.1 REMOTE EXCAVATION AND RETRIEVAL BY BACKHOE TELEOPERATION

First demonstrations of backhoe teleoperation using the TSEE were performed in December, 1992, at ORNL. The TSEE was used to excavate and retrieve a 55-gallon drum buried in a test pit near the Robotics & Process Systems Complex at ORNL. The objective of this demonstration was to meet an intermediate milestone on the development path toward major system demonstrations scheduled in 1993. This first demonstration included teleoperation of the backhoe only, and utilized an early version of the Graphical User Interface (GUI) along with an intuitive hand-controller. In addition to presenting both the DOE and PM-AMMOLOG sponsors a hands-on demonstration of technical status, this event also heralded the first opportunity for representatives from various DOE sites involved in remote excavation to discuss development and demonstration plans with representatives from three branches of the Department of Defense (DOD). Attendees included representatives from the U.S. Air Force (Tyndall Air Force Base), U.S. Navy (Indian Head EOD), and U.S. Army (Redstone Arsenal EOD School and PM-AMMOLOG). The demonstration successfully illustrated the improved dexterity of the TSEE rate controls compared to manual operations and user friendliness of the intuitive hand controller and GUI. Figure 1 shows a photograph of the TSEE with the 55-gallon drum test piece cradled in the backhoe bucket. References 1-5 provide additional information on the system status at the time of this demonstration.

Fig. 1 Telerobotic Small Emplacement Excavator photograph during a backhoe teleoperation demonstration in December 1992 at ORNL. Retrieval of a buried 55-gallon drum was used to simulate buried waste or unexploded ordnance retrieval.

Fig. 1 Telerobotic Small Emplacement Excavator photograph during a backhoe teleoperation demonstration in December 1992 at ORNL. Retrieval of a buried 55-gallon drum was used to simulate buried waste or unexploded ordnance retrieval.

2.2 OVERBURDEN REMOVAL AND BURIED WASTE RETRIEVAL

In June and July, 1993, a series of waste retrieval technology demonstrations sponsored by the DOE OTD Buried Waste Integrated Demonstration (BWID) was completed at the BWID Cold Test Pit at the Idaho National Engineering Laboratory (INEL). The two primary objectives of these tests were to evaluate and demonstrate feasibility of remote overburden removal and remote excavation of simulated buried waste. A test pit was prepared with four different cells each approximately a cube with 10-ft sides. Simulated waste of different types or configurations were placed in each cell. Tests were performed measuring overburden removal rates and dig depth accuracies. Then a "containment" structure was erected and further tests conducted focusing on retrieval tasks. Along with these retrieval tests BWID conducted dust suppression and contamination control experiments as well. The retrieval tests included rate and accuracy measurements as well as human factors performance tests. Results of the BWID tests may be found in reference 9. The front loader was used for remote overburden removal tests at INEL. A 10-min videotape has been prepared describing the TSEE system including operational footage [7].

2.3 EXPLOSIVE ORDNANCE DISPOSAL TECHNOLOGY DEMONSTRATION

A series of tests similar in nature to the buried waste tests described above but focused on EOD tasks was completed September 13-17, 1993, at the U.S. Army Redstone Arsenal, Huntsville, Alabama. The demonstration was hosted by the OMMCS with the objective of evaluating the performance of the TSEE and demonstrating the feasibility of remote explosive ordnance disposal. This report describes and summarizes this EOD demonstration and the findings of the human factors tests performed using primarily instructors and students at the Redstone Arsenal EOD School.

3. SYSTEM DESCRIPTION

The major components constituting the TSEE system; the vehicle, portable control station and communication system, and the GUI are described below. An inventory of the significant parts required to developed the TSEE is provided in Appendix F of reference 6. Essentially, all design drawings required for fabrication and assembly of the TSEE are provided in Appendix E of reference 6.

3.1 EXCAVATOR AND ON-BOARD SYSTEMS

The SEE is a commercially available system, built for the U.S. Army by Freightliner, Inc. The SEE has both a backhoe and a front-end loader as shown in Fig. 1. The backhoe is an adaptation of the Case 580E commercial backhoe and the vehicle is a modified Mercedes Benz Unimog truck.

The ORNL modifications to the vehicle center around modifying the hydraulic and pneumatic systems for computer control as shown in Fig. 2. High-performance proportional valve components were used to improve dexterity over the existing manual valves. Each joint of the backhoe, stabilizers, and front loader were modified for computer control. Hydraulic pressure sensors at each joint provide limited indications of force exerted by the backhoe. This force feedback has been converted to a measure of torque and provided as an operator display at the control station. Remote driving capabilities were achieved by installing pneumatic actuators on the clutch, power take-off, and shift levers of the vehicle (the SEE is available with manual transmission only). A hydraulic motor was attached to the steering wheel to provide remote steering capability. The backhoe and front-end loader have been outfitted with customized resolvers for measuring joint position. This feedback is required for robotic operation and also used to drive a graphical model of the backhoe in the GUI.

Fig. 2 Computer control architecture schematic for the hydraulic and pneumatic actuator systems of the TSEE.

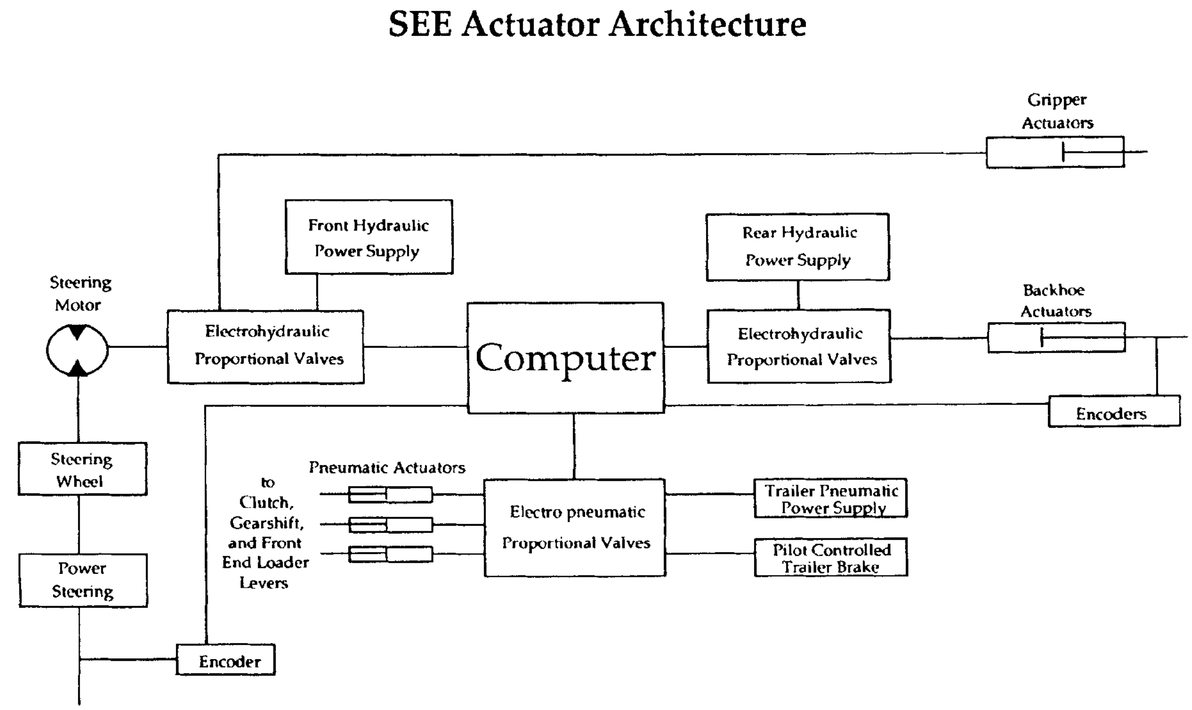


Fig. 2 Computer control architecture schematic for the hydraulic and pneumatic actuator systems of the TSEE.

Remote viewing is provided by three color television cameras mounted on the vehicle. Two cameras with pan, tilt, and zoom mechanisms are mounted on the truck body behind the cab (Fig. 1) and provide a view either forward to support front loader operation and remote driving or backward to support backhoe operation. A fixed focus color camera mounted on the backhoe boom allows the operator to look either directly into the dig zone or into the cupped bucket, depending on the position of the bucket. Though the boom camera was not a part of the original design concept, it has proven to be extremely useful during operation. For a small amount of additional effort and cost, this camera could be replaced with pan, tilt, and zoom capabilities as well.

A number of additional sensors were mounted onboard to provide operator feedback or vehicle status data (Fig. 3). Tilt sensors were mounted on the vehicle to provide both lateral and longitudinal tilt measurements. During the overburden removal tests described above, a global positioning system (GPS) antenna was mounted on the cab and a second GPS antenna was provided at the control station for differential position measurements. A microphone was mounted onboard to provide audio feedback to the operator. System status indicators such as fuel level, water temperature, computer enclosure temperature, battery charge, and oil pressure were also provided and interfaced to the onboard computer system. A water-tight enclosure was mounted on the vehicle to house the onboard computer, radios, sensor interfaces, and signal processing equipment. A solid state air conditioning unit was mounted on this enclosure to protect the controls equipment from overheating during hot weather operations. Sufficient heat is generated by the hardware in this enclosure so that operation in cold weather would not be hindered.

Fig. 3 The TSEE has a large number of on-board sensors to provide operator feedback.

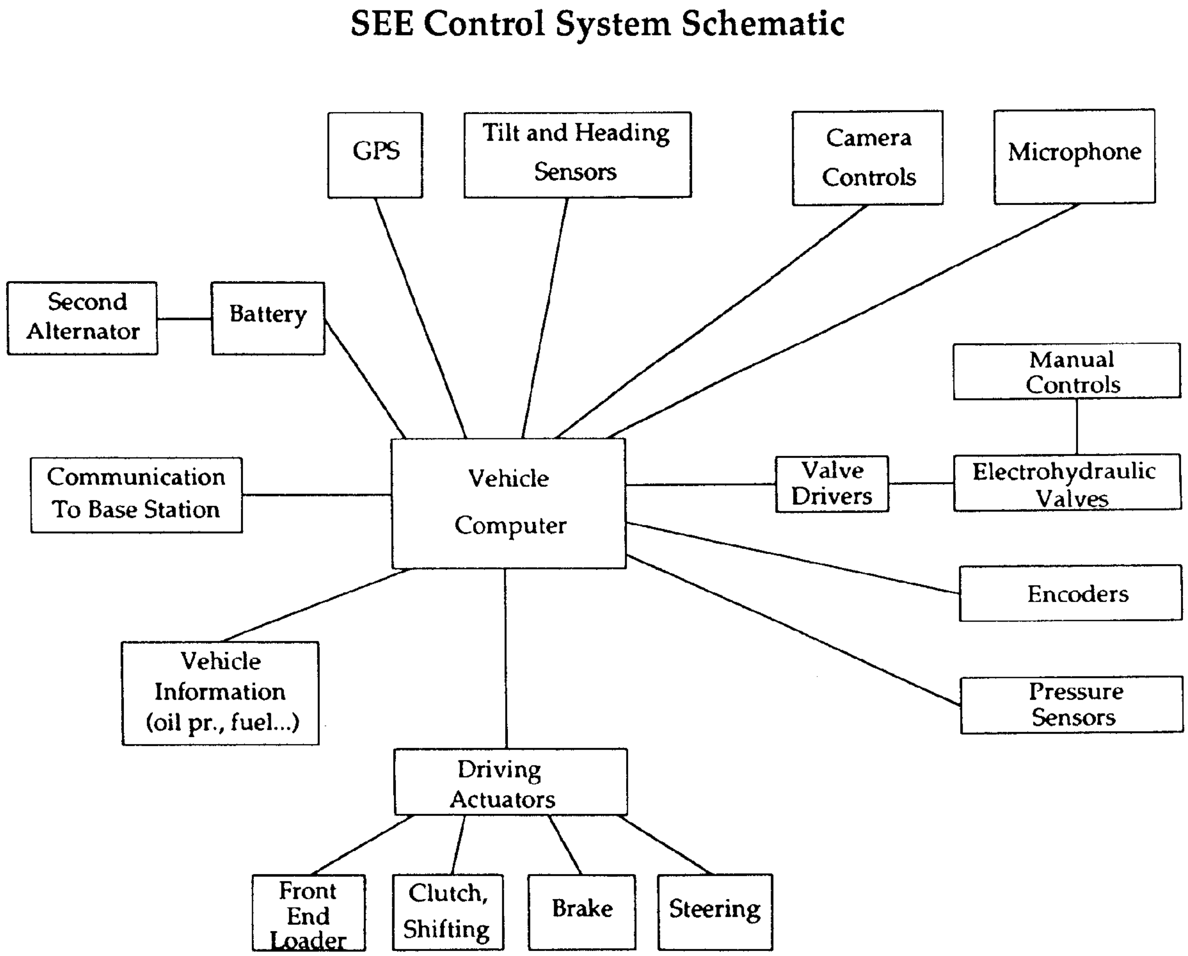


Fig. 3 The TSEE has a large number of on-board sensors to provide operator feedback.

3.2 CONTROL STATION

The base station for the TSEE is a compact and rugged console which packs all the necessary computers, control input devices, computer monitors, and television screens into a single, easily transportable “suitcase” controller.

To meet the military’s need for a field deployable system, capable of being operated from a foxhole rather than a command trailer, major changes in the existing backhoe manual controls were required. An intuitive hand controller was developed to replace the two foot pedals and five hand levers of the manual system. The assembly consists of a single axis joystick for the left hand and a three axis joystick on its side for the right hand. The arrangement is shown in Fig. 4.

Included on the control panel is a set of joysticks for camera pan, tilt, zoom, and focus controls; buttons for backhoe startup and shutdown; and a trackball for menu selections on the computer screen. During the Huntsville demonstration, an emergency shutdown button, which turns off computer control of the vehicle, was provided separate from the controller. This “panic button” has since been built into the control panel itself.

Another area of the control station that required a significant design effort was the monitor screens for the computer and the video cameras. By using active matrix liquid crystal displays (LCD), a dramatic size reduction was achieved compared to the traditional cathode ray tubes (CRT). The computer display is a 25 cm, 256 color LCD made by Sharp Electronics that is presently being used in several laptop computers. This 640 x 480 pixel screen has proven to be a good compromise between the suitcase size limitations and the display requirements. The video is displayed on two 23 cm color LCDs, also made by Sharp. To reduce the size of the workstation computer imbedded in the console, the workstation was implemented with a Sun-compatible VME CPU card made by Themis. The system is presently equipped with a disk drive and keyboard to support software development activities, although these will not be present in a fielded system. Also contained in the VME rack is an analog-to-digital converter for the joysticks and an extra computer for communications processing.

Finally, the collection of hardware was mounted in a suitcase-shaped container made by the Zero corporation. This watertight, military grade container is 47 x 27 x 52 cm and contains the hardware mentioned above plus the power supplies and the fiber optic communication hardware. As shown in Fig. 4, the computer screen is embedded in the main container, the two video screens are embedded in the container’s front lid, and the joystick panel is stowed under the container’s rear lid. Power for the station is 24 volts DC which can be supplied from another military vehicle battery or from a 110V to 24V supply. If necessary a battery pack could be adapted for field use.

The communications system between the vehicle and base station consists of two microwave video channels and an Ethernet data radio. The data radio is a sophisticated, spread spectrum Ethernet packet radio made by Telesystems. Vehicle

Fig. 4 The control station for the TSEE is a compact and rugged suitcase-sized controller, convenient for field use.

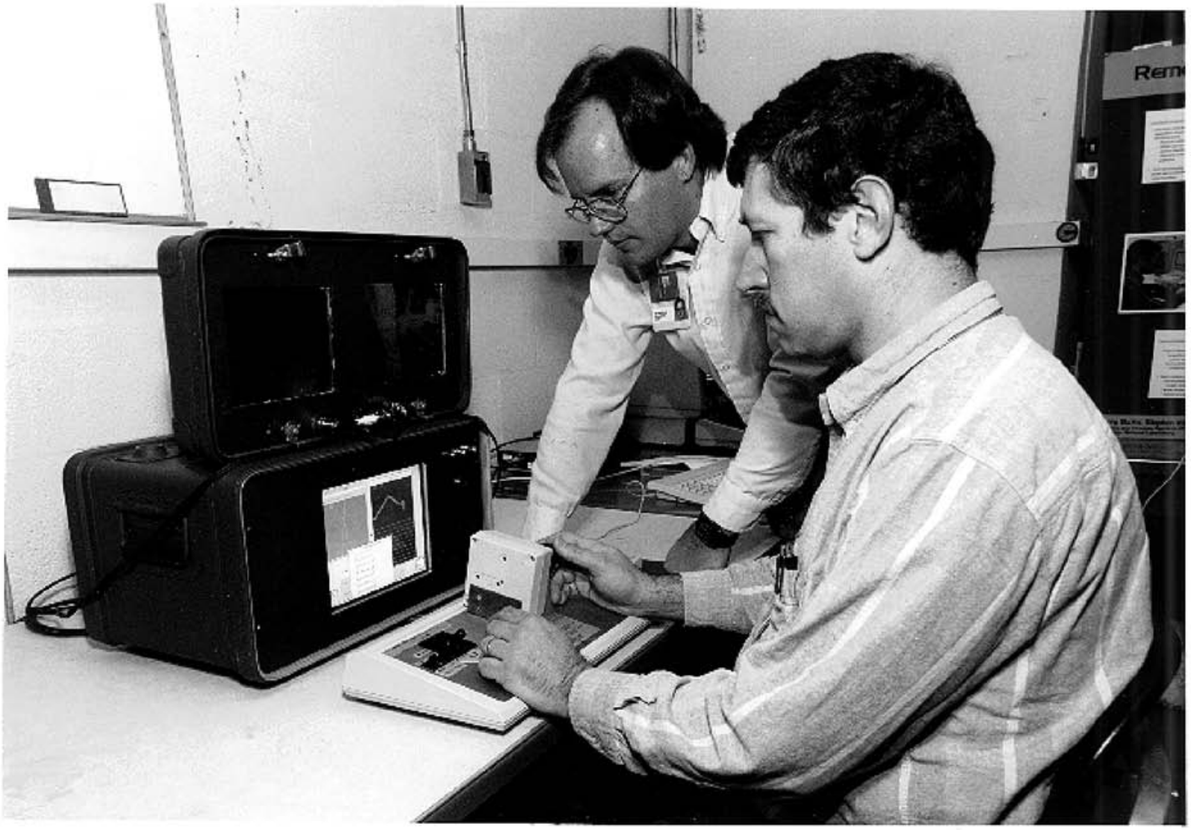


Fig. 4 The control station for the TSEE is a compact and rugged suitcase-sized controller, convenient for field use.

status and position indicators, audio from the work site, and video displays are transmitted from the vehicle to the control station over the data link while command and control data are transmitted from the control station to the vehicle. Transparent operation of the Ethernet radio enables flexible operation for the computer system. A remote kill switch is also enacted through a separate radio frequency. The frequencies used for radio communications were reserved for this project at Oak Ridge and three other DOE sites where related experiments are planned. For U.S. Army applications where a secure communication channel may be required, a fiber-optic bundle may be used. The fiber optic cable reel would be stowed on the SEE vehicle. At the time of the EOD demonstration at McKinley Range, the fiber optic communications option was not yet implemented and dedicated radio frequencies were not made available; therefore, communications were implemented using coaxial cable.

3.3 GRAPHICAL USER INTERFACE

The GUI on the TSEE is designed to supplement the information that an operator gets through the cameras. The GUI provides the remote driver with audio and video feedback, graphics displays, position indicators, torque and tilt information, as well as dig depth and camera direction. A remote operator who is limited to two camera views is deprived of much information about the work area that an on board operator would have. To help the operator recover from the loss of depth perception, the GUI has animated displays that allow an operator to obtain information on relative positions of objects by modeling some features that cannot be seen. In addition, the GUI provides other highly useful operational status data that are not available to an operator sitting on the backhoe performing excavation tasks but must be monitored by a second operator or require the primary operator to interrupt digging. The GUI is also used for job setup providing services for camera positioning and selection, dig depth limits, control system modes, auto dump mode setup, and graphical markers.

Using menu selections, the operator can select from a number of windows that provide information or act as control panels for operation of various features of the system. The system was designed to be portable, which means that the GUI will be used on a small display. Each window provides selected information and can be accessed the operator using the mouse and operator controls provided with the windowing system on the computer. Allowing the operator to choose which windows are on screen and which windows are in front negates the need for a large screen displaying all the information all the time.

The main window of the GUI is a plan view of the work area. This plan view is an animated graphic that provides a top down view of the work area. The outline of the vehicle is drawn in the bottom center of the view and the position of the backhoe is drawn as if it were viewed from above.

The second most frequently used display is the side view display. This display shows the position of the excavator as if it were viewed from the side. The operator can see the position of the bucket, boom and dipper links that position the bucket. The ground is drawn with lines at 1-ft intervals allowing the operator to judge the bucket depth. The bucket is modelled in sufficient detail that the operator can use the graphic to adjust the bucket to the proper angle for the task at hand.

Using icons in the plan view, an operator can reposition the two vehicle cameras by dragging sight lines on the screen with the mouse. If the dig zone or dump zone positions are known or can be determined by “touching” them with the backhoe, then a graphical marker can be placed in those locations. A corresponding marker is automatically drawn in the side view window and is coordinated with the plan view marker so that it appears at the appropriate distance from the swing pin and appears only when the excavator is over the mark on the plan view. Markers in the side view graphic can be moved up or down in depth and can be adjusted in size if the operator knows the approximate size and location of the object being represented, for example, either a buried object or perhaps an above bin or obstacle. This feature allows the operator to return to the same position in a dig or judge how high a receptacle is in a retrieval operation. It can also be used to mark known positions of buried objects since the markers show their position in feet when selected with the mouse.

Other information available from the side view includes the torque indicators. These provide an indication of the force being exerted at each excavator joint and attempt to replace the sense of feel that a remote operator loses. This information is provided by means of a pie chart located on the joints. The portion of the pie that is colored in, along with the direction that is colored in, provides the torque information. At a preset limit, the color changed to from gray to red and the system beeps an audio alarm indicating a high torque is being applied. The pie chart is scaled such that the pie is full at the point that the vehicle would be picked up or moved by the excavator. The beeping will start at that point calling the operator’s attention to potential need for adjusting the load.

The third graphic window is the instrument panel. This is a column of edge meters drawn with labels and scales. The meters represent the following engine and vehicle operating data: a tachometer; fuel, oil pressure, and water temperature indicators; voltage indicators for the battery and auxillary battery; box temperature indicator; and indicators displaying the status of the air to the brake system and replacement brake. In addition to the normal indicators, the tilt sensors (pitch and roll) and the steering wheel angle are provided for use during remote driving.

There are several dialog boxes that can be selected from the menu. A dialog box is a small control panel that appears on screen, allowing the user to input information and select operating modes. One dialog box controls the dig depth. The operator uses a slide bar to select the depth of an artificial dig floor. The operator can also set the slope of that floor on two axes. A line that reflects the depth and slope of the dig floor is drawn on the side view window. Other dialog boxes are provided for auto dump setup, and camera manual controls.

4. TECHNOLOGY DEMONSTRATION OF THE TSEE - MCKINLEY RANGE, REDSTONE ARSENAL, HUNTSVILLE, ALABAMA

4.1 DESCRIPTION

The TSEE was transported to Redstone Arsenal from Oak Ridge, Tennessee, by flat bed truck on September 13, 1993. The vehicle was positioned in a field about 200 ft beyond an instructional building at McKinley Range. The control station was located in this building in an area large enough to accomodate the TSEE technical team, test participants, onlookers, and provide space for completing the human factors evaluation forms. The fiber optic Ethernet communications system had not been implemented at the time of the demonstration and provision for dedicated radio frequencies was not pursued, therefore, communications with the vehicle was accomplished using coaxial cables. By the end of the day, September 13, the system was unloaded, setup, checked out, and ready to commence testing.

During the demonstrations on September 14 and 15, approximately 40 EOD specialists including students and instructors from the OMMCS were briefed on telerobotic operation of the TSEE and given an opportunity to operate the system for a mock bomb retrieval exercise. The soldiers' experience in manual operation of the SEE ranged from 0 to 1000+ hours. Upon completion of the mock EOD tasks, participants completed an evaluation of the system including human factors performance data. A sample evaluation form is provided in Appendix B of reference 6. A briefing and hands-on demonstration was held on September 16 for the OMMCS Commandant, Colonel Stirling, and other distinguished guests. A 48-min videotape was made of the briefings presented including footage of system operation [8]. Interested persons may request a copy of this tape from the authors or from the project sponsor PM-AMMOLOG.

Demonstration participants were required to accomplish remote overburden removal and retrieval of dud bombs buried at a depth of up to 2.5 meters. Training prior to initiation of the task was limited to a very brief description of the functions on the control panel, brief overview of the GUI, and less than a minute per person of hands-on training with the hand controller. Because of the user-friendliness of the controls and intuitiveness of the hand controller, no further instruction was required for the participants to begin the test tasks.

4.2 EOD TEST RESULTS

Results of the human factors evaluations are presented graphically in Appendix C of reference 6. Written comments provided by these participants are included as Appendix D of reference 6. Response for two summary level questions on the human factors survey are presented in Fig. 5. The other charts in Appendix C of reference 6 address specific components of the system. Many of the participants, particularly the officers and other distinguished guests, opted not to complete an evaluation form. A summary of the results is presented below. Of the 35 participants who completed evaluation forms, 8 had less than 1 hour of experience operating the TSEE manually, 14 had experience ranging from 1 to 99 hours, 10 had experience ranging from 100 to 499 hours, and three participants had 500 or more hours of experience.

4.3 SUMMARY OF HUMAN FACTORS PERFORMANCE DATA

4.3.1 Task Accomplishments

Approximately 70% of participants found that using the remote system was as easy or easier than using the normal system, see Fig. 5. The average experience using the manual system for these participants was 39 hours. Of the participants with less than 1 hour experience in manual operation, 7 out of 8 found the task easier to accomplish remotely.

Of the 35 participants queried, 100% stated they could accomplish the required demonstration task most of the time and that the errors they encountered were small and unimportant to task accomplishment. Only 5 of the 35 participants stated that the task was not easily accomplished, while 30 of the 35 found that it was easily accomplished. For the 5 participants who found the task difficult, manual operations experience ranged from 10 to 75 hours for 4 of them while 1 person was very experienced, having about 800 hours.

4.3.2 Hand Controller

Eighty percent of participants found the TSEE hand controller was as easy or easier to use than the SEE manual controls. With a minimum of training using the intuitive hand controller, one hundred percent of evaluation participants were able to accomplish the mock EOD tasks.

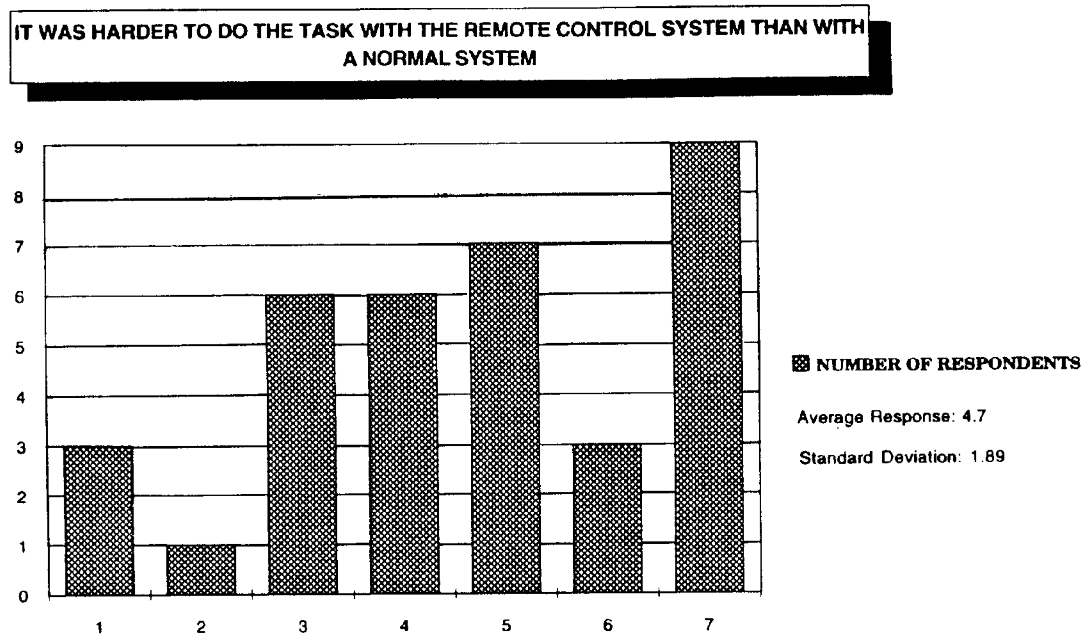
4.3.3 Realism

When asked whether the television screens and sound system made participants feel like they were working at the remote site, only eleven percent gave a negative response. Experience in manual operation for these respondents averaged 109 hours, and ranged from 60 to 200 hours. Approximately 90 of all participants stated that sound from the remote area was important during the task. Demonstration participants were evenly split when asked whether they felt like they were really out there on the excavator while performing the task remotely.

4.3.4 Displays

Nearly 70 of participants found that the GUI provided all the information they needed. Twenty-nine percent of participants stated that some displays (temperature, tilt, joint position, torque, status, etc.) were not useful. Due to the short duration of the retrieval tasks, participants did not need some of this information to complete the task. Had the exercise been more prolonged, more of the status indicators would have been useful; for example, fuel level, oil pressure, and water temperature.

Fig. 5 Sample Human Factors Data from the Telerobtic Small Emplacement Excavator unexploded retrieval tests conducted at Redstone Arsenal.



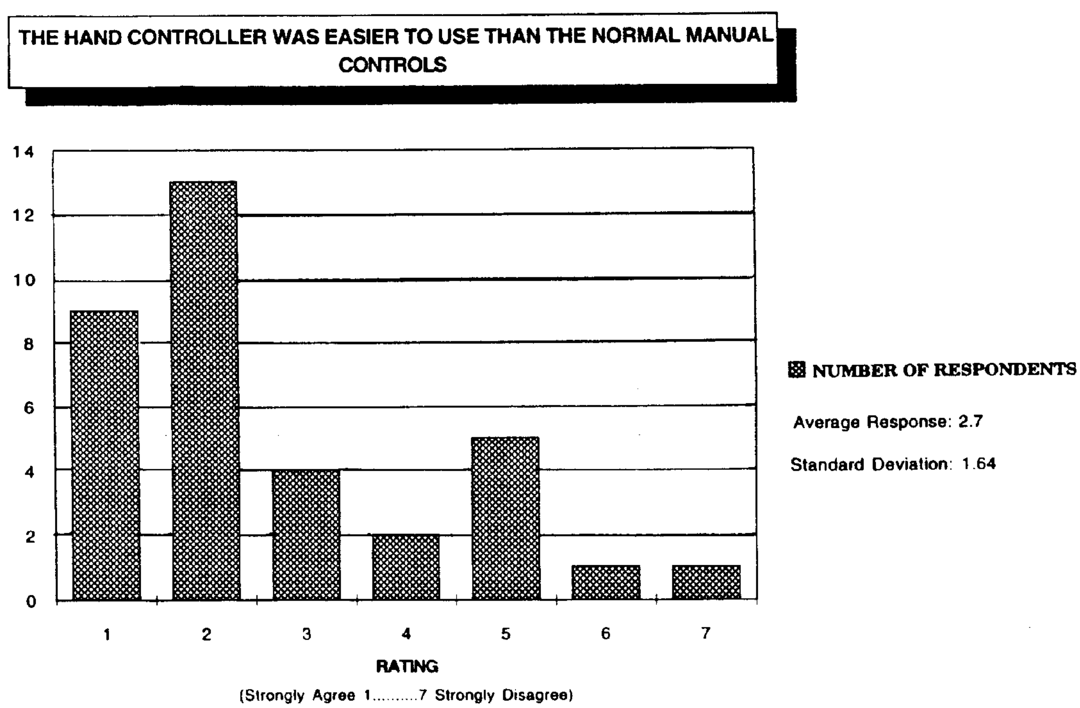


Fig. 5 Sample Human Factors Data from the Telerobtic Small Emplacement Excavator unexploded retrieval tests conducted at Redstone Arsenal.

Forty percent of participants stated that they could not have accomplished the task without the animated backhoe display, while forty-three percent stated they could. Seventeen percent were indifferent. Of those participants who felt that they could have accomplished the task without the display, experience with SEE operation averaged 200 hours. Only one participant responded that the backhoe display was not useful, while greater than 60% found it extremely useful.

Camera usage varied significantly among demonstration participants. On average, the boom camera was used the most, followed closely by the GUI animated backhoe display. Approximately 60% of camera usage was split among these two displays. Participants relied more heavily on the right TV camera than the left. This was due mainly to the fact that the dig area was slightly right of center behind the backhoe. Sun angle and glare on the cameras also contributed to camera selection. Usage of other parts of the GUI such as the status windows was negligible for most participants.

Approximately 74% of respondents felt that the vehicle mounted cameras were in the best location to do the assigned task. When asked whether the TV monitors were the best size for the work or if they were too small, responses were evenly split.
None of the participants responded that the camera controls were hard or confusing to use and less than 20% of respondents stated that the TV picture quality was not good enough to do the job well.

4.4 Other Demonstration Results

Although OMMCS requirements focused on backhoe telerobotic operation, the evaluation participants frequently commented that they could make good remote use of the front loader as well. The front loader is often used for stabilization and lifted during minor repositioning of the vehicle. Appendix D of reference 6 provides a summary of comments made by the evaluation participants.

5. CONCLUSIONS

The technology demonstration of the TSEE for remote EOD operations at Huntsville, Alabama, provided both feasibility and human factors data that will be used to evaluate the TSEE design and potential applications of the telerobotic system. A significant finding of the demonstration is the fact that individuals with and without experience in manual operation of the vehicle were able to accomplish the assigned task easily with very little instruction. The intuitive hand controller coupled with the GUI makes an otherwise complicated task, requiring hours of training, simple and easily accomplished. The demonstration has shown that the TSEE can be a valuable tool for EOD operations, accomplishing the required tasks remotely with an increase in dexterity and negligible productivity losses due to remote operation, while decreasing risk to operators.

Based on the results of the demonstration, the following design modifications were implemented: The emergency computer control shutdown button was added to the control panel; a trackball was added to the control panel (eliminating the need for a mouse and eliminating the keyboard in field deployments); and automatic camera switching capability was added (cameras can be set to switch automatically to left or right cameras based on the position of the boom). Additional modifications which are under consideration include adding color to the vehicle status displays on the instrument panel and replacing the current boom camera with a zoomable camera with automatic iris adjustment.

6. FUTURE ACTIVITIES

A grappling end-effector and associated additional hand controller are currently under development at the ORNL for integration with the TSEE. The new end-effector and controls development are sponsored by DOE and will allow the system to manipulate a variety of tools. The grappling end-effector is initially intended to manipulate rigging equipment to facilitate the retrieval and removal of concrete waste containment casks. A HhotF field test of the system is scheduled for August 1994 at the Hill Cut Test Facility in Solid Waste Storage Area 6 at ORNL. A field demonstration of chemical munitions cleanup is planned during FY 1995 at Aberdeen Proving Ground. Other follow on activities related to environmental applications demonstrations, range clearance, combat engineer, battle field cleanup, and EOD concept employment evaluations by the U.S Army have been discussed but are not underway at this point.

Prior to fielding the TSEE system in large numbers, a few modifications are recommended. Chief among these modifications is replacement of the developmental computer hardware on-board the vehicle with more compact and ruggedized processors. This can be accomplished by burning the software into a Programmable Read-Only Memory (PROM) and removing the onboard disk drive. The PROM will not only prevent inadvertent software changes, but will also decrease the size required for the onboard computer, controls and communications enclosure.

7. ACKNOWLEDGMENTS

The authors wish to express their appreciation to all those who assisted in the completion of the development and demonstration of the TSEE. In particular, thanks go to Steven Herman of OMMCS who provided direction, feedback, and support to the ORNL staff from the inception of the TSEE project. Thanks to the OMMCS Commandant, Colonel Stirling, and his staff for hosting this EOD demonstration, especially those involved in operation of the McKinley Range at the Redstone Arsenal. We also wish to thank Dr. John Draper of ORNL for assistance preparing the human factors evaluation form and Lesli Alcorn and Kyra Donnell for assistance in the data compilation, analysis, graphing, and many other aspects of preparing this summary report. We appreciate the cooperation of the two DOE program managers, Dr. Linton Yarbrough and Dr. Jaffer Mohiuddin, who, jointly with the U.S. Army PM-AMMOLOG, sponsored the development and demonstration of the TSEE as a remote excavation technology test bed. Finally, we would like to thank the demonstration participants for their cooperation and the benefits of their experience. This demonstration event was a great opportunity to get prototype system operation and design feedback from the real experts, the intended operators.

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